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An Overview of NDE Methods For Thick Composites And A Proposal For Analysis of Computed Technology Data

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13. Non-Destructive Evaluation (NDE) techniques are used for detecting manufacturing flaws, detecting service induced damage, dimensioning of objects and characterizing materials. Many methods are available for composite materials inspection and yet no single method is able to resolve all the damage due to the complexity of the material. This report will review many of the techniques currently being used for the investigation of composite materials. The importance of determining the damage modes is critical to the effort for predicting the residual strength in thick composites. The study of composite materials is a multidisciplinary field, encompassing the study of mechanics, materials and NDE in order to effectively understand the damage accumulation process and the resulting behavior of composite structures.

This report will discuss some of the information which can be gained from further study and analysis of Computed Tomography (CT) images representing the damage modes present in impact damaged thick composites, in particular, woven roving S-2 glass panels. A proposal for automating the calculation of the volume of damage in the composite panels will be presented as well as a proposal for separating the different damage modes corresponding to damage types such as matrix cracking, delaminations and fiber breakage.

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Introduction

Nondestructive evaluation (NDE) techniques which can accurately assess the type and extent of internal damage to thick composites are necessary in order to provide input to residual strength analysis of composite materials. Although there are destructive techniques, such as sectioning and photomicroscopy, which can identify the various types of damage, the residual strength cannot subsequently be experimentally tested.

There are many NDE techniques available today which are capable of detecting various types of damage by measuring temperature changes, changes in signal attenuation or distortions in signal transmission[1,2]. Techniques such as thermography and acoustic impact technique are not effective for internal inspection of thick glass composites but are useful for surface or near surface damage. Acoustic and ultrasonic techniques are able to detect damage but are not able to differentiate between damage modes unless they are known *a priori*. Traditional radiography, acoustic and ultrasonic methods can determine the depth of a flaw, however, damage obscured by other flaws cannot be detected. The images obtained using NDE methods are often not of sufficient quality to distinguish damage types without enhancing the image. Even high resolution, full gray-scale images are usually subject to interpretation and the information in these images may not be fully exploited. Some of the most frequently used methods, along with their strengths and weaknesses, will be discussed in the following section.

Computed tomography (CT) reconstructs a full 3-D image of the inspected object and is therefore able to detect damage through the entire thickness. Research in other methods, such as thermography and ultrasonics, is being conducted to implement 3-D reconstruction [3,4]. CT has been used in the medical field for 30 years and as a result, 3-D reconstruction and image enhancement techniques are more advanced than those corresponding to other NDE techniques. This report will present a proposal for automating a damage volume calculation, thereby eliminating variability due to interpretaion from the outcome. A proposal for separating the different damage modes corresponding to damage types such as matrix cracking and delaminations will also be presented.

Nondestructive Damage Characterization

The following methods are in use or in development for the NDE of composite materials. Each method is described briefly along with its strengths and shortcomings. Concise surveys of current state-of-the-art NDE techniques may be found in References [1-2]. The aim of these techniques is to obtain information about the internal material structure in order to detect and differentiate defects and damage. Among internal structures of interest are manufacturing defects such as voids, porosity, cracks and ply debonding, service induced damage due to environmental effects such as corrosion and moisture, and service loads resulting in delaminations, fiber breakage, matrix failure and general material fracture.

Acoustics/Ultrasonics

Ultrasonic techniques involve introducing high frequency mechanical vibrations or an acoustic pulse into a material. The inspection geometry can be either through-transmission or one-sided pulse-echo. Through-transmission inspection measures the signal strength that is transmitted through the material which will show reduced strength where a defect exists. The pulse-echo technique measures the returning signal, which will be reflected back earlier when flaws, such as delaminations,

are encountered. Pulse-echo can measure the depth of flaws, however if one flaw is obscured by another, the second flaw cannot be detected.

Acousto-ultrasonics uses a specially formulated acoustic pulse and measures the form of the returning or transmitted wave. These techniques require contact, either direct or by immersion in a coupling fluid, with one or both sides of the object being tested. Laser ultrasonics is based on excitation and detection of sound through the use of laser light and does not require direct contact. Emerging technologies based on laser-diode pumping promise more compact and hence portable laser ultrasonic equipment. Methods of enhancing the images are limited, however, research in this area is continuing and has great potential[1,2,6]. Figure 1 shows a sample ultrasonic image containing a square metal shim positioned at the mid-plane of a 1" thick S-2 glass woven roving laminate.

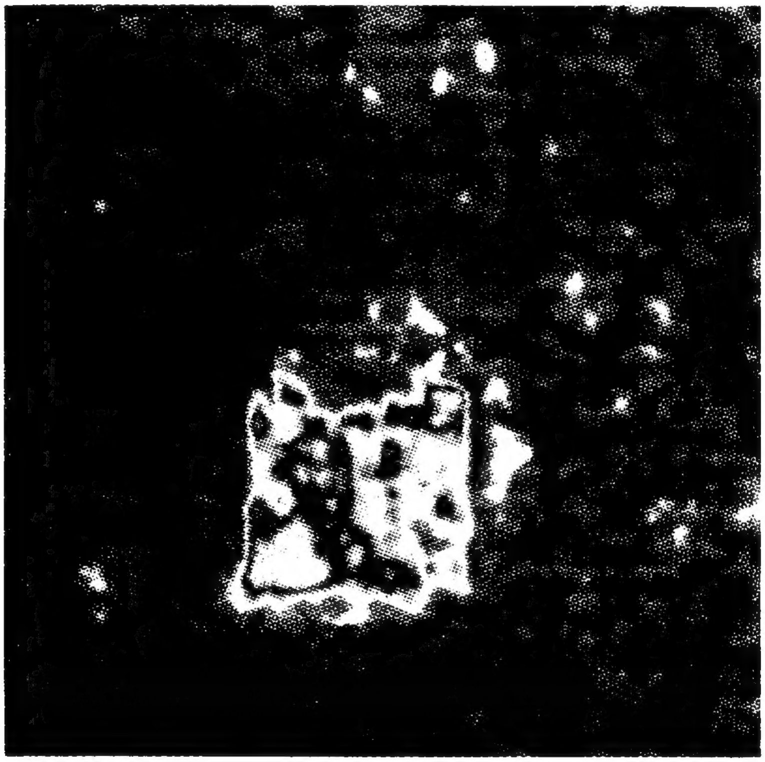

Figure 1. Ultrasonic image of a thick composite panel with simulated damage.

The standard tap test uses either a coin or a special hammer to detect delaminations or disbonds near the surface. Traditionally, this method has been subject to the interpretation of the individual inspector, but current research is focusing on using an acoustic emission sensor to evaluate the response of the tap in order to obtain objective results [7].

Thermography

Infrared (IR) or thermal imaging relies on the fact that an application of heat to the surface of a material will result in surface temperature changes. If the material is without defect the heat will diffuse uniformly, while defects in the material will show variations as the heat diffuses. Two methods for IR imaging are in use. The one-sided approach, in which the front surface of the

material is heated and temperature variations are recorded via an IR imaging system on the same side. The two sided method applies heat to one side and uses IR imaging on the other side, with the two sided method being slightly more sensitive. Thermography works well with complex geometry since contact is not required.

Another type of thermal imaging is vibrothermography, which introduces energy to the specimen and uses an IR system to record the resulting temperature variations. The method of introducing energy limits applications, however it is effective for complex geometries [8]. It is also difficult to find methods for reproducing thermal gradients in composites. Advances are being made in signal analysis tools and systems with greater sensitivity[1,3]. Current sensors can detect temperature changes on the order of 0.001^oC. This gives a resolution comparable to a common strain gauge. However, sensitivity decreases rapidly with depth of flaw, and as a result the inspection of thick composites is not very effective. Figure 2 depicts a thermogram showing the stress profile of a loaded metallic specimen with an open hole.

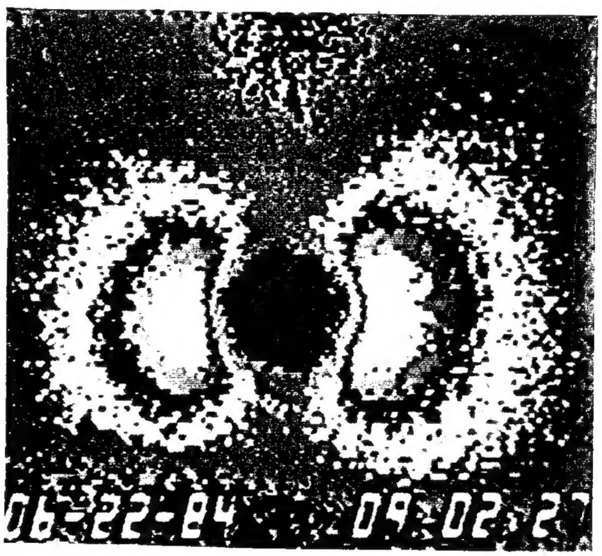

Figure 2. Thermograph of stresses around an open hole in a loaded specimen.

Holography and Shearography

A hologram is formed by the superposition of two wave fronts, produced by an object beam and a reference beam and recorded, usually on photographic film. A fringe pattern is produced when the specimen undergoes a small displacement as a result of stressing it by thermal or mechanical means. A defect-free specimen will produce a smoothly varying fringe pattern, while a defect will cause an anomaly in the fringe pattern. In shearography, only one beam is used and the returning object beam is doubly imaged, with one of the images slightly shifted or 'sheared', rather than using a separate reference beam.

Subsurface defects on the order of 3 mm at a depth of 18 mm can be detected using these

methods [10]. Current research is focusing on developing a methodology for detection and characteriztion of defects using a fringe-spacing analysis method which measures the fringes to determine flaw location and size [1,9,10].

Radiography

Radiography relies on x-rays or other energy sources and images the differential absorption of the energetic particles. Flaws or defects that allow particles to pass, be absorbed or scattered can be imaged. Typical systems have achieved sensitivities of better than 1.0% to 2.0% in thickness or density variations. Radiographic imaging methods include x-ray backscatter which uses the portion of the attenuation due to scattering to determine information about material properties, such as density changes, which indicate defects. Reverse geometry is a real-time radioscopy system, shows improved sensitivity and resolution and may soon be transportable. However, for thick materials, deep flaws are obscured by internal features above them.

Microwave

Microwave techniques function similarly to radiography. Flaws are detected through the differential absorption or backscattering of the energy applied from a beam of microwave energy. Nonconducting composites are best suited for this method. Recent advances particularly in the development of new equipment in the millimeter domain have made this method very promising, however it may be several years until it is developed sufficiently.[1,11]

Computed Tomography

CT has even better resolution (less than 0.1%) than conventional radiography. CT uses x-rays, or other energy sources, to scan a planar slice through a three dimensional object and employs mathematics to reconstruct the interior plane of the object. In this way a full 3-D image can be built, enabling interior damage to be seen. Other techniques collect data from a full 3-D region and any slice can be selected for viewing on a computer. Supervoltage CT and high-resolution x-ray CT are current topics of research and will offer even more accuracy and detail in the future [12,13]. There are portable CT systems available but they are effective only for relatively small objects. CT is an expensive and time consuming technique, but it is capable of detecting almost all types of defects.

A Proposal for the Analysis of CT Scans

This is a proposal of a procedure to automatically calculate the damage volume in CT scans of impact damaged composite materials. Damage volumes were used in [5] in an attempt to correlate it with residual strength. The volume calculation in Reference [5] was done by applying a median filter to the image to highlight the damage. Then a threshold was applied to the filtered image until it started to break up and then reversed until the the image appeared correct to the operator. A volume was calculated by counting the pixels inside the thresholded area and multiplying by the pixel area and the thickness of the CT slice. This method is subject to operator interpretation and is therefore not rigorous. Automating the procedure will eliminate the subjective aspects of the

volume calculation. Techniques to extract damage modes captured in the CT image are also being proposed. The ability to identify damage modes is essential as input to an analysis of residual strength. The following subsections will describe the available data and proposals for an automatic volume calculation and segmenting of damage modes.

Description of Data

The data consists of CT scans from the study conducted in Reference [5]. The panels used in that study were S-2 glass reinforced plastic (GRP). They measured 20 inches by 20 inches by approximately 1.7 inches. Each panel consisted of 63 to 69 plies of woven roving S-2 glass. The panels were subjected to ballistic impact and then nondestructively evaluated using CT.

Automatic Volume Calculation

Figure 3. shows a CT image of impact damage in a GRP panel. This grayscale image offers an excellent view of the damaged interior. A grayscale CT image can be interpreted as a density map, that is, the x-ray attenuation coefficient correlates directly to the density of the material being scanned. A histogram of the x-ray attenuation coefficient versus freguency of occurrence for a damaged panel is presented in Figure 4. Information from an undamaged panel can be used to determine the amount of damage in a damaged panel.

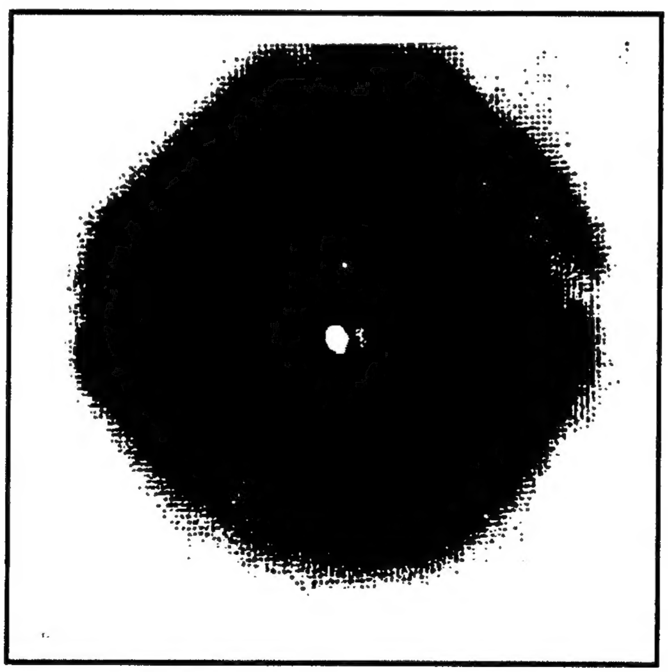

Figure 3. CT image of damage in a composite laminate.

Damaged areas have different densities than undamaged material and appear as different clusters in a histogram. The histogram in Figure 5 displays the characteristic material signature of an undamaged GRP panel. The remainder of this section will elaborate on a procedure using this information.

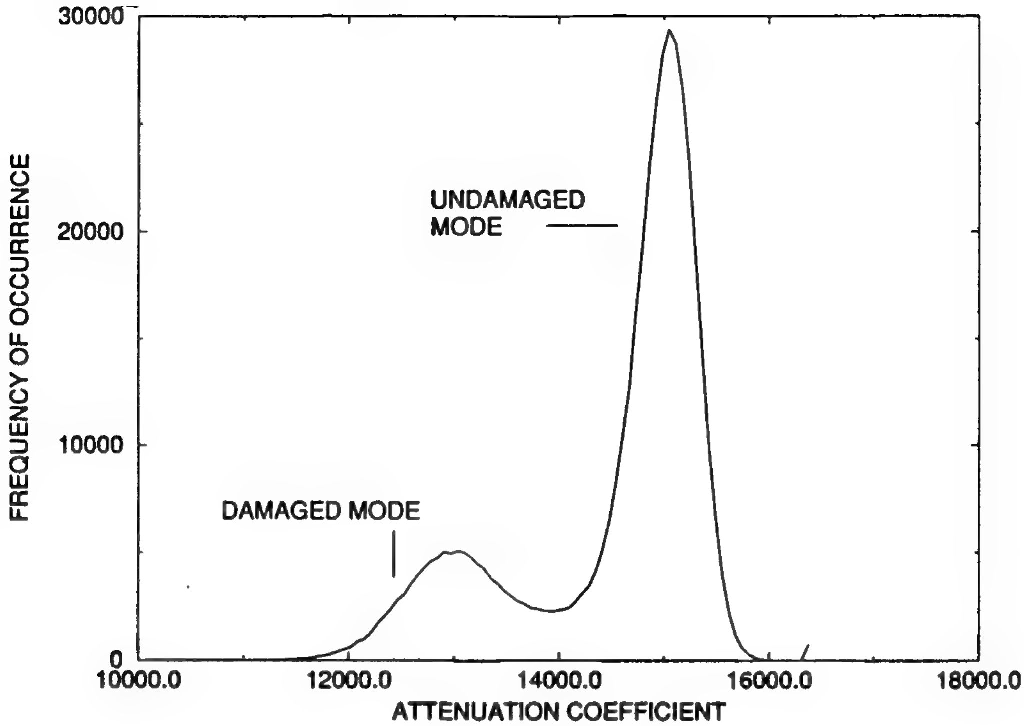

Figure 4. Bimodal histogram depicting modes in a damaged panel.

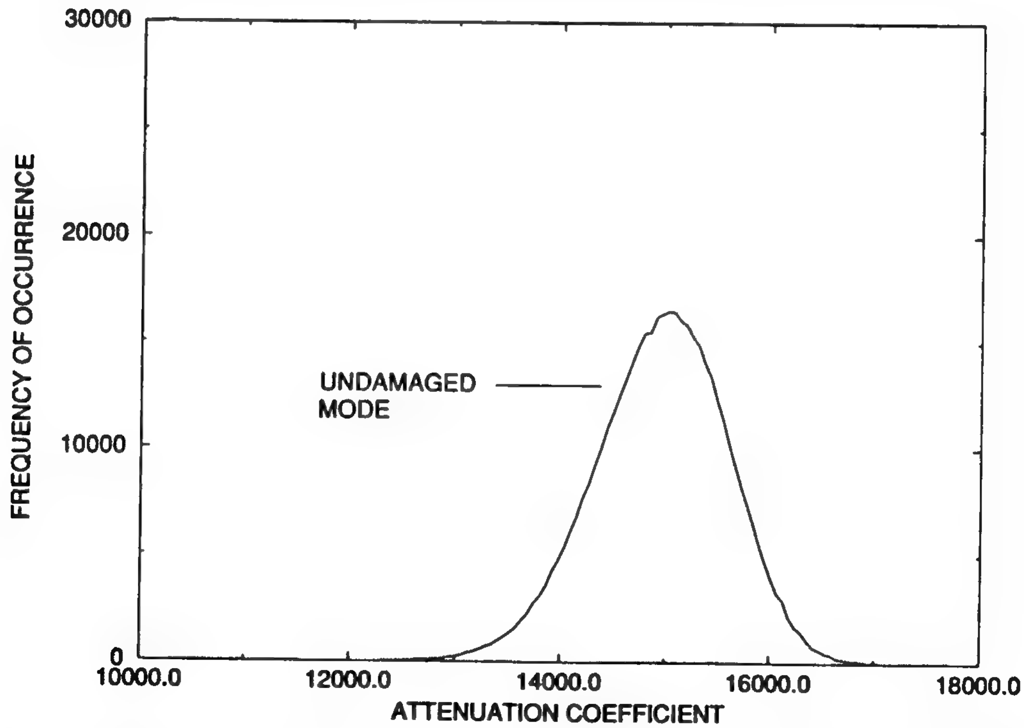

Figure 5. Histogram depicting characteristic material signature of an undamaged panel.

Automating the volume calculation begins by using one of the numerous edge detectors available in image processing, such as contour following, Hough transform and principal curves [14,15]. The damaged area is isolated in the image using one of these edge detectors. Studying the bimodal histogram in Figure 4. reveals that the rightmost mode represents the undamaged material as

shown in Figure 5. As an example, in Figure 6, K5 is a slice from the undamaged panel (K), and P19, P20 and P21 (panel P) are CT scans from a panel with very little damage (the damage appears as a spike at the left end of the graph). The mean and standard deviation corresponding to the undamaged portion of panel P are approximately the same as those in the undamaged panel K. Some of the difference between the undamaged modes in histograms can be attributed to variation in the composite material. For the sake of robustness, it would be neccessary to take all the slices from an undamaged panel and obtain an average histogram which will then be subtracted from the histograms of damaged panels. Using statistical techniques, this mode will be removed from a damaged histogram leaving only the information describing the damage. Since the resulting histogram is simply a count of pixels corresponding to the different damage modes, it will be an accurate assessment of the amount of damage. The number of pixels in the damage mode divided by the total number of pixels gives a percent of volume damage for that slice. Once a correct count has been found, the pixels corresponding to damage can be turned on (or off) in the image to provide an approximate view of the damage in the panel.

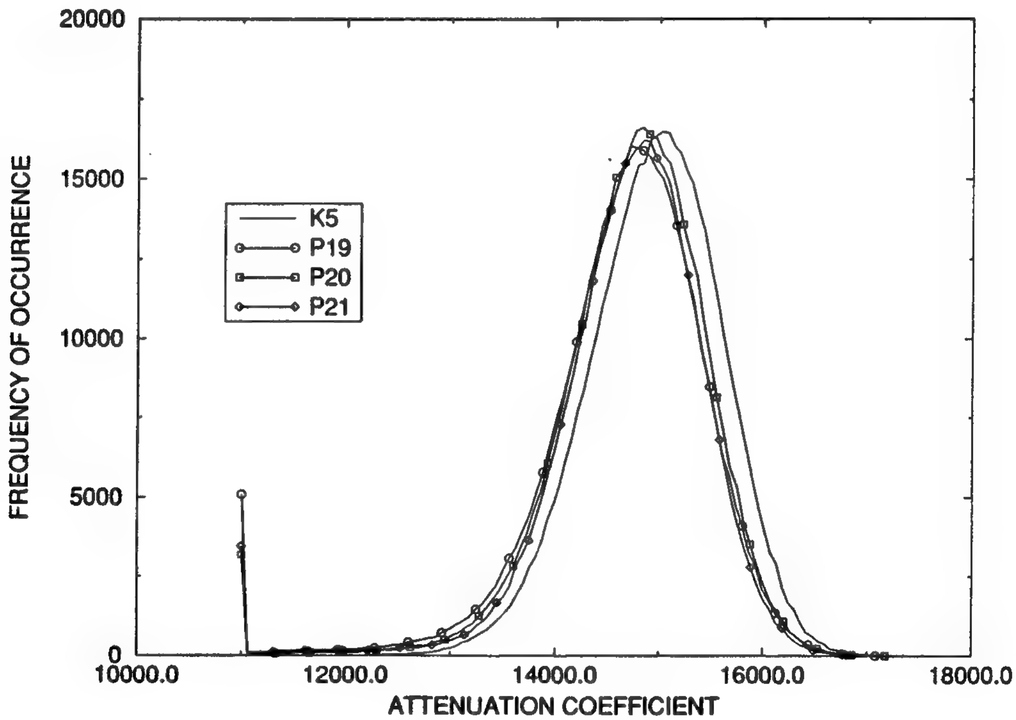

Figure 6. Comparison of histograms of an undamaged panel (K) to a damaged panel (P).

Segmenting of Modes

The techniques proposed in the previous section for removing the undamaged mode will be extended to segment other modes occurring in multimodal CT scans. Figure 7 shows a multimodal histogram corresponding to a CT image of a damaged panel. Figures 8, 9a and 9b show images which represent the individual modes from the histogram in Figure 7. Figure 9a shows an image representing mode 1 and Figure 9b corresponds to mode 2 of the histogram in Figure 7. Figures 9a and 9b demonstrate that the different modes correspond to specific regions which needs to be correlated with specific damage types.

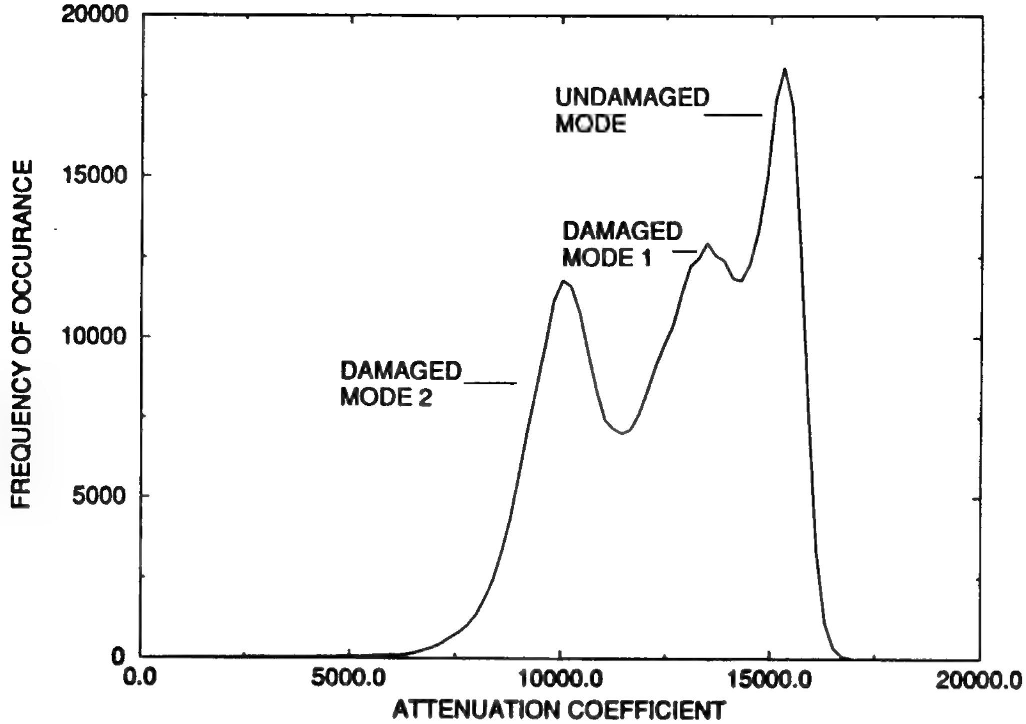

Figure 7. Multimodal histogram of a damaged panel.

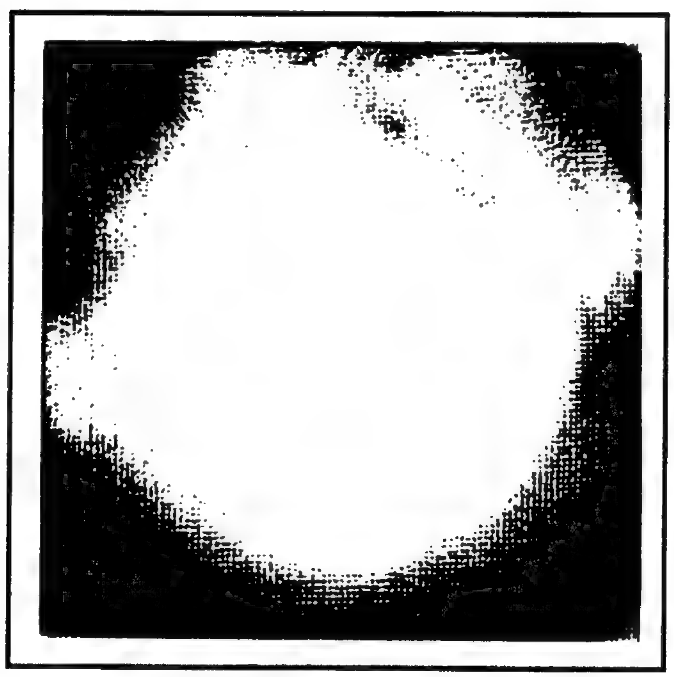

Figure 8. CT image corresponding to undamaged mode in a damaged panel.

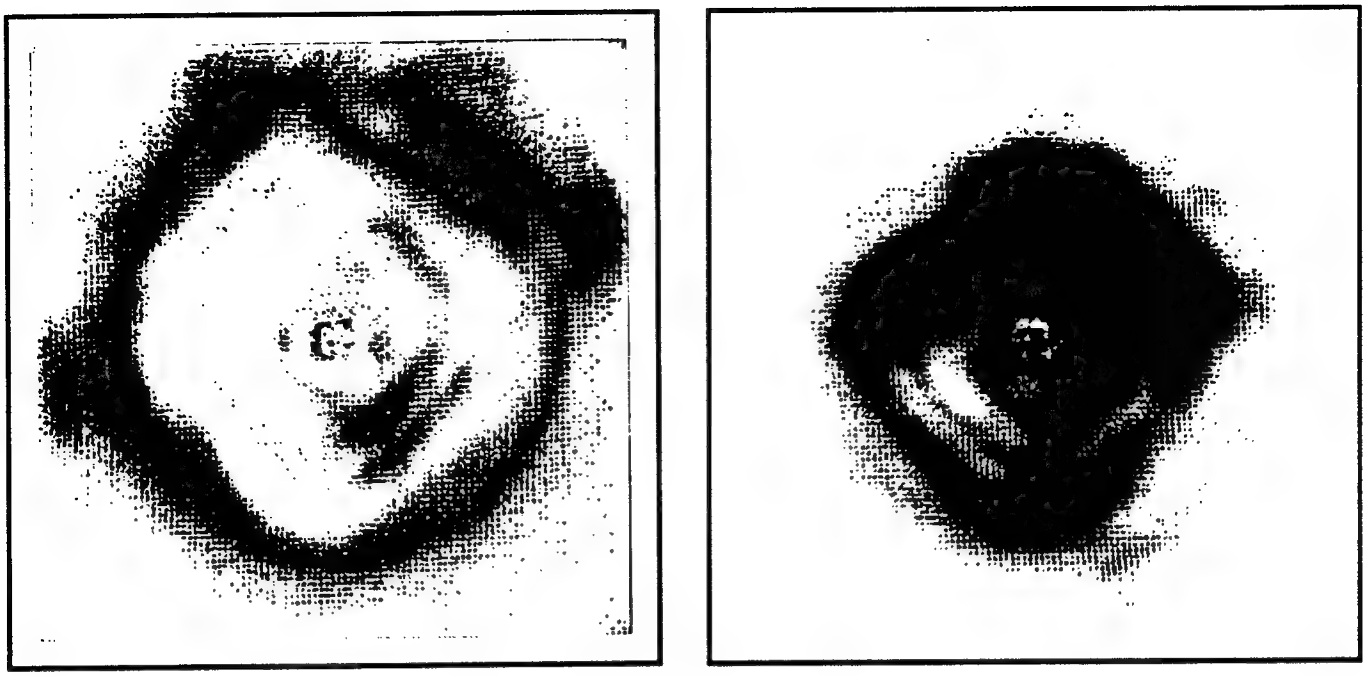

Figure 9. a. CT image corresponding to damage mode 1 in histogram of 8.
b. CT image corresponding to damage mode 2 in histogram of 8.

Recommendations

It is recommended that these proposals be carried out as detailed above. The automatic volume calculation is a simple, accurate way to determine the volume of damage in a panel and can be used in additional studies such as those in Reference [5]. The capability of segmenting modes offers great potential benefit as input to residual strength analyses [16]. It is recommended that damaged panels be subjected to photomicrosopy for specific identification of damage types. It is also suggested that cross sectional CT scans be taken, which would more readily identify delaminations, and correlate with the modes in the histograms. The correlation will provide the capability to identify various damage modes, while still retaining the ability to conduct subsequent residual strength tests, and in addition, to assess repair/no-repair options for composites in service applications.

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